FRACTURE TOUGHNESS OF COMPOSITE LAMINATES THROUGH NOTCHED BEND TESTS : A J - INTEGRAL APPROACH

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KUMAR SARANGARAJAN

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CERTIFICATE

This is to certify that the thesis titled 'FRACTURE TOUGHNESS OF COMPOSITE LAMINATES THROUGH NOTCHED BEND TESTS : A J-INTEGRAL APPROACH', by KUMAR SARANGARAJAN is a record work carried out under my supervision and has not been submitted elsewhere for a degree.

B.D. Agarwal
B.D. AGARWAL
Professor
Department of Mechanical Engg.
Indian Institute of Technology
Kanpur-208016

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NOMENCLATURE

A	Area
a	Crack length
d	Generalised displacements
F	Generalised force
G	Energy release rate
J	J-integral
J_{1c}	Critical value of J-integral in mode 1
LEFM	Linear Elastic Fracture Mechanics
l	Length of the specimen
P	Load
r	Near tip crack field length parameter
S	Boundary of a two dimensional body
S_T	Portion of boundary where traction is prescribed
SEN	Single Edge Notched specimen
T_i	Traction vector
t	Thickness
U	Potential energy per unit thickness
u_i	Displacement vector
U_T	Total potential energy
U_{nc}	Energy without crack
V_f	Fibre volume fraction
W	Strain energy density function
w	Width

X_1, X_2	Co-ordinates
σ	Stress along load direction
σ_{ij}	Stress tensor
ϵ	Strain along load direction
Γ	J-integral contour
ν	Poisson's ratio
QIL	Quasi Isotropic Laminates
CPL	Cross Plied Laminates
ERI	Energy Rate Interpretation
EP	Estimation Procedure

ABSTRACT

Fracture behaviour of Quasi Isotropic Laminate under bending have been investigated. Fracture toughness tests were conducted on Single Edge Notched specimens subjected to bending load. J-integral was evaluated using both Energy Rate Interpretation and Estimation Procedure. Estimation Procedure is found to be easy and simple and the value of J-integral obtained by it match very well with that obtained by Energy Rate Interpretation. Fracture toughness tests on Quasi Isotropic Laminate under tension were also conducted. This was done to validate that J_{1c} is independent of a/w.

CHAPTER - I

INTRODUCTION

1.1 COMPOSITES:

Composite materials are a combination of two or more distinct materials so as to achieve certain physical properties not realizable individually. Their light weight and high specific-strength yield them as useful structural material in space vehicles. In addition, they also posses useful properties such as high stiffness, toughness, vibration, fatigue and corrosion resistance and high temperature performance. Although significant weight savings, paramount in transportation engineering are possible, composites have gone far beyond being simply lighter than conventional materials. They offer real structural advantages with almost unbounded potential. The ability to tailor a particular matrix-material to suit prevailing environmental conditions whilst maintaining adequate reinforcement to withstand applied loading is unquestionably an attractive proposition.

The use of composite materials in the Nuclear Industry has increased with the diversification of

applications of this industry to the present day world. The uses vary from the more commonly known applications, such as the fuel elements used inreactors, to lesser known applications such as, fuel utilized in radio isotopic thermal electric generators for space applications. Many of the composite materials used in the Nuclear Industry are similar to those used in other industries. Typical are the structural materials which require high mechanical strength at elevated temperatures.

Future use of composites in Nuclear Industry will include the use of high performance glass, silica, graphite or other fibres incorporated into materials chosen for a particular application.

1.2 FRACTURE MECHANICS OF COMPOSITES:

Stress analysis techniques based on effective moduli or other continuum mechanics approches to fibre/ matrix laminates have provided rules for selecting lay-up angles and laminate geometries to obtain specified stiffness. However, few rules exist which have a basis in a failure analysis. If composites are to be used to their fullest extent as engineering materials, it will be necessary to know in advance their limits in load bearing applications. To do this, predictive techniques for the various failure modes that can occur in such applications

must be established.Fracture mechanics, the discipline concerned with failure by crack initiation and propagation, is a natural tool to use for this purpose.

Fracture of composites is highly complex in nature involving any one or a combination of the following: breaking of the fibres, fibre pull-out, debonding between the fibres and matrix, matrix cracking etc. The problem of characterising fracture behaviour of composite materials is challenging as the crack-propagation in them differ substantially from the cracks in homogenous isotropic materials which exibit self-similar crack growth. The additional complexities in composites underscore the need for parallel or combined experimental and theoretical analysis. Fracture mechanics of composite materials, together with its initiation, propagation and controlling parameters, represents a significant problem.

Fracture toughness of a material represents its resistance to fracture by crack propagation. There are different methods and procedures to obtain fracture toughness namely the R-curve approach and the J-integral approach. The R-curve approach has been studied more widely for metallic materials and has been extended to composites [1-4] in the last decade. Investigators have

considered similarities between a damage zone and crack extension. The instantaneous crack length is estimated by a compliance matching procedure. This approach is somewhat tedious and time consuming.

As stated earlier composites, in general, do not exibit self-similar crack extension. Instead, a damage zone is formed. Damage zone is a region of stable crack growth at the crack tip. In such a case characterisation of the crack-tip parameter calculated without focussing attention directly at the crack-tip would provide an easier method of analysing the fracture. The J-integral proposed by Rice [5] is such a parameter. Its value depends on the near-tip stress-strain-field. However, the path independent nature of the integral allows an integration path taken sufficiently far from the crack-tip to be substituted for a path close to the crack-tip region. The basis for J-integral is provided by the works of Rice and Rosengren [6]. They have shown that a singularity in the stress and strain does exist at the crack-tip which is uniquely dependent upon the material flow properties. Mc.Clntock [7] has demonstrated that the crack-tip stress and strain field can be described in terms of J-integral. The use of J-integral as an elastic plastic fracture criterion has been

discussed by Broberg [8] from an analytical stand point. Begley and Landes [9, 10] through extensive experiments have shown the applicability of J-integral as a fracture criterion for metals. It is well known that, in composite materials, microcracks at the fibre matrix interface appear at very low loads due to the stress concentrations produced by the fibres lying perpendicular to the load. It is probably this unavoidability of microcracks that has deterred the researchers from exploring the applicability of the J-integral as a fracture criterion for composite materials. Recently, Patro [11] and Agarwal, Patro and Kumar]12] had investigated fracture behaviour of randomly oriented short glass fibres reinforced epoxy resin. In their work, fracture tests were conducted on Single Edge Notched specimens and J-integral was experimentally evaluated using energy rate interpretation. They have developed an extrapolation technique and have also shown that J_{1c} is independent of a/w if appropriate extrapolation procedure is used for small a/w.

In the same lines, Srinivasan [13] has also done extensive work in this field. He had tested both Quasi Isotropic Laminates (QIL) and Cross Plied Laminates (CPL) subjected to tensile load. He has experimentally

obtained the value of J-integral using energy rate interpretation. He has also obtained J_{1c} corresponding to a critical displacement. The J_{1c} obtained by him for CPL is a constant value for all a/w while for QIL, he has obtained two different values of J_{1c} for two ranges of a/w. The value of J_{1c} obtained by him for QIL for a/w > 12.5 is almost double the value of J_{1c} for a/w $\leq$ 12.5. But, Agarwal, Patro and Kumar [12] have shown that J_{1c} is independent of a/w if appropriate extrapolation procedure is used for small a/w. Due to this reason, Srinivasan's results for QIL raised some doubts about their accuracy. Therefore more fracture tests in tension to determine experimentally the value of J_{1c} were performed on QIL by the author. These have been discussed in detail in Chapter IV.

Yet another author Khanna [14], has also used energy rate interpretation to obtain the value of J-integral. He had tested specimens made from Fine, Singles yarn glass fabric reinforcement and coarse, plied yarn glass fabric reinforcement.

Extensive theoretical work has been done by Babu [15] and Mishra [16]. They have also worked on the principle of energy rate interpretation.

1.3 SCOPE OF THE PRESENT WORK:

All the study on short fibre composites done so far by Patro [11], Srinivasan [13], and Khanna [14] were for specimens subjected to Tensile load.

The present work is done on specimens subjected to Bending Load. Both Quasi Isotropic and cross plied laminates have been tested. Both these laminates with varying crack lengths have been tested under bending load.

The value of J-integral have been obtained experimentally both by energy rate interpretation as well as by Estimation Procedure.

Quasi-Isotropic and cross plied laminates are often used as structural materials and hence studied.

CHAPTER - II

EXPERIMENTAL PROCEDURE FOR J-EVALUATION

The J contour integral has been proposed as a parameter that characterizes the stress and strain field ahead of a crack in a linear or non-linear elastic material subject to monotonic loading [5]. This integral is currently arrousing considerable interest as a potential toughness characterizing parameter, this is particularly so far low and medium strength materials for which the measurement of toughness by means of linear elastic test procedures generally requires large specimens. For a linear or non-linear elastic material, the value of J at first crack extension J_c is equivalent to the strain energy release rate or fracture surface energy term G_c. In the presence of significant plasticity, this energetic interpretation of J is lost, although several investigations [17,18] have indicated that J_c may still adequately characterize the local crack-tip conditions for fracture initiation.

2.1 PROCEDURES FOR DETERMINING J-INTEGRAL:

J-integral as proposed by Rice [5] is a two dimensional energy line integral:

$$J = \int_{\Gamma} (w\, dx_2 - T_i \cdot \frac{u_i}{x_1}\, ds) \qquad (2.1)$$

where, Γ is any contour travelling in a counter clockwise sense and enclosing the crack tip as shown in Fig. 2.1. T_i is the traction vector, u_i is the displacement vector, s is the arc length along Γ and w is the strain energy density.

Further, Rice [5] has also shown that the J-integral is equal to the change in potential energy for a virtual crack extension i.e.;

$$J = - \frac{U}{a} \qquad (2.2)$$

where, U is the potential energy per unit thickness.

J-integral can also be determined by Estimation Procedures (EP). Various Estimation Procedures (EP) have been proposed as a means of simplifying the complex evaluation of procedure for J which was originally advocated for fracture toughness specimens by Begley and Landes [9]. These approximation procedures rely mainly on the proven path independence of the integral for linear and non-linear elastic materials and thus permit the contour to be removed conveniently to the specimen

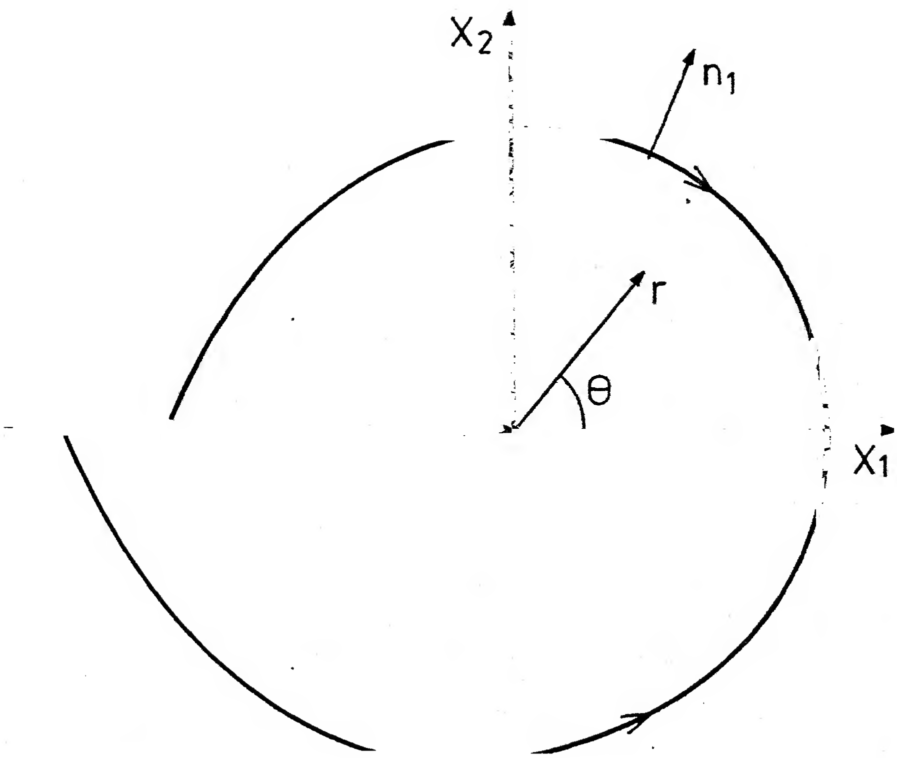


Fig. 2.1 Crack tip co-ordinate system and arbitrary lime integral.

extremities. It is to be emphasized, therefore, that most of the estimation procedures assume that the deformation is confined to the region ahead of stress concetrator and that this deformation field is associated with homogeneous material.

A very good summary and comparison of procedures has been given by Chipperfield [19]. He has given as many as 9 methods and compared their relative merits.

Table (1) presents a comprehensive and most suitable procedure for three types of specimens viz; Single Edge Notch Tension Specimen, Compact Tension and Three Point Bend Specimen.

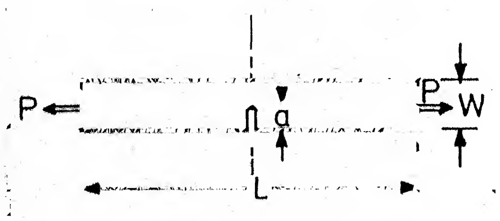
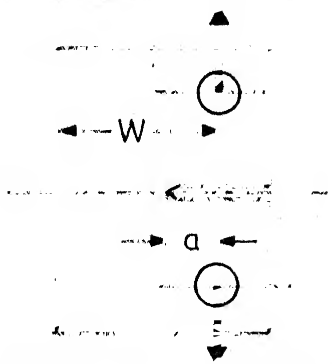
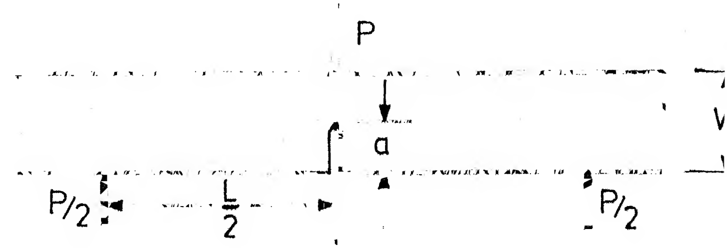
2.2 PROCEDURE USED IN THE PRESENT STUDY:

In the present work for experimental determination of J by Energy Rate Interpretation (ERI), use is made of eqn. (2.2). The estimation procedure used in this study is the one developed by Rice et al [5] which is the method (3) in Table 2. Where,

$$J = \frac{2U_c}{Bb} \qquad (2.3)$$

where U_c is the total energy U_T in the specimen minus the energy U_{nc}, that would normally exist in the specimen if the specimen did not have a crack. Equation (2.3) can be re-written into the form most often used to

TABLE : 1

SEN TENSION	COMPACT TENSION	SEN THREE POINT BENDING
		
$J = -\frac{\partial V}{\partial a}$ defl. (method 1)	$J = \frac{2U}{B(W-a)}$ (method 3) or $J = \left[\frac{2}{B(W-a)}\right]\left\{n_1 P\Delta + n_2 U\right\}$ (method 5)	$J = \frac{2U}{B(W-a)}$ (method 3) or $J = \left[\frac{P\Delta - 2U_{nc}}{B(W-a)\{1+\alpha(P/P_{max})^2\}}\right]$ (method $U_{nc} = \left(\frac{0.12P^2S^3}{BEW^3}\right)\left[1.04 + 3.28\left(\frac{W}{S}\right)^2(1+\nu)\right]$

estimate the value of J for bend type specimens.

$$J = \frac{2A}{Bb} \tag{2.4}$$

where A is the area under the load versus displacement curves (Figs. 4.6 and 4.7). In the development of this equation Rice assumed that the specimen was in pure bending q, at least, that the contribution due to tension was negligible.

2.3 COMPARISON OF EP AND ERI:

Though comparison cannot be made, yet, a two distinct advantages exist in the determination of J-integral by Estimation Procedure (EP) over that Energy Rate Interpretation (ERI) technique, and they are:

1. Simple and easy to calculate.
2. Possibilities of inaccuracies in approximating to a straight line the energy versus crack-length value used to calculate the value of du/da in the ERI technique is eliminated.

It is also to be noted here, that a number of authors [20,21] have reported that problem exist when using equation (2.4) for bend bar specimens. Strawley [22] had shown that there is a considerable difference when using the total energy as compared with the energy due to the presence of a crack. This has been further illustrated by Landes, Walker and Clarke [23], who have

inferred that the total energy U_T should be used when estimating the value of J for three point bend specimens.

However, the successful application of J_c values to the assessment of defects in structures will ultimately rely on the ability of a preferred analysis procedure to produce accurately or moderately conservative toughne's values.

CHAPTER - III

EXPERIMENTAL DETAILS

The present studies were performed on glass fibre reinforced epoxy laminates supplied by the 3M Company of U.S.A. Short fibre composites which are isotropic in the plane have earlier been analysed. As a next step the Quasi-Isotropic Laminates (QIL) of configurations $[0/\pm 45/90]_{2s}$ and Cross-Ply Laminates (CPL) of $[0/90]_{4s}$ configuration have been tested under Bending Load.

3.1 PROPERTIES OF LAMINATES:

The stress-strain behaviour of the laminates are shown in Figs. 3.1 and 3.2. The properties of both Quasi and Cross Ply Laminates are presented in Table 2.

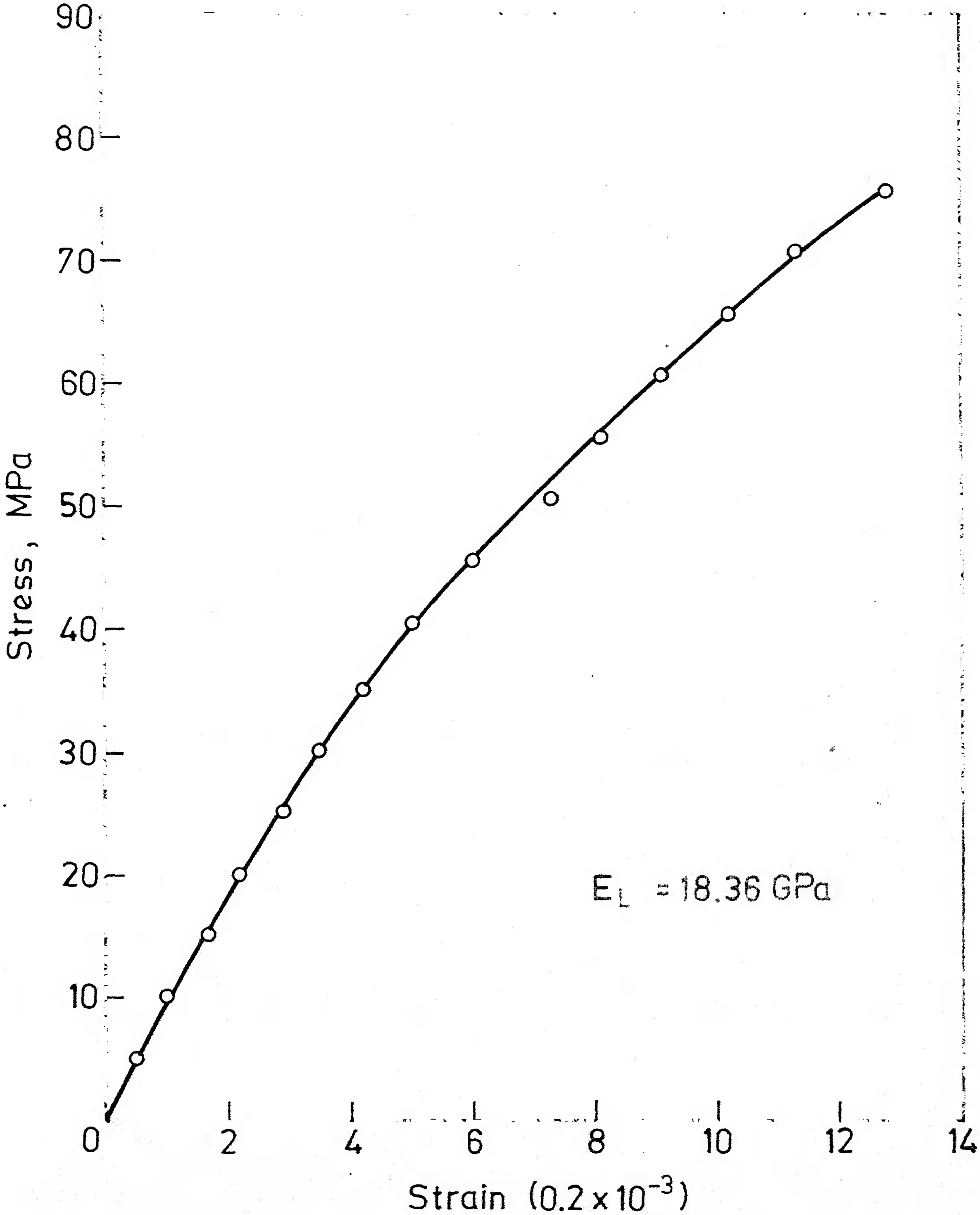


Fig. 3.1 Longitudinal stress-strain curve for quasi-isotropic laminate.

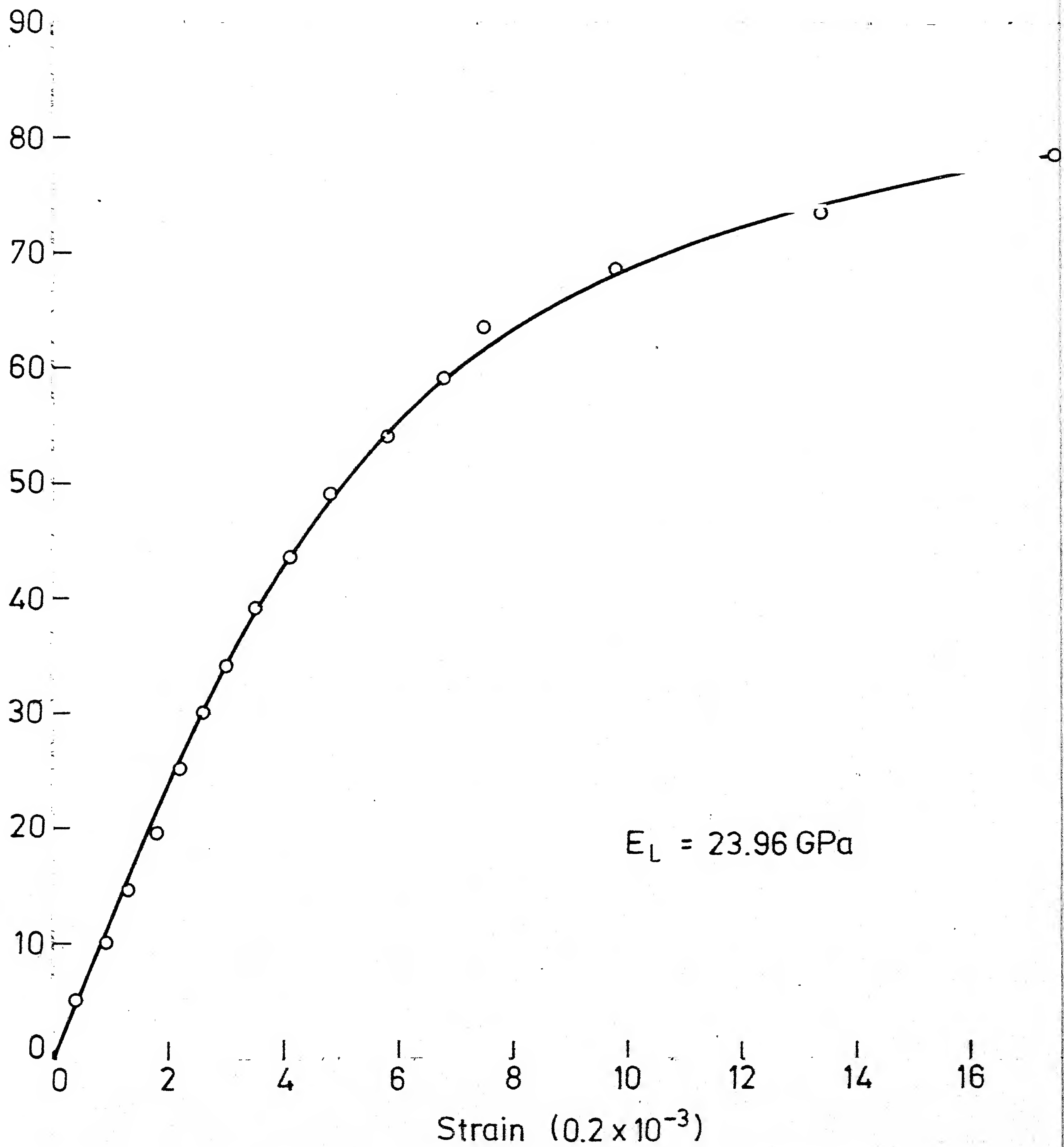


Fig: 3.2 Longitudinal stress-strain curve for cross-ply laminates

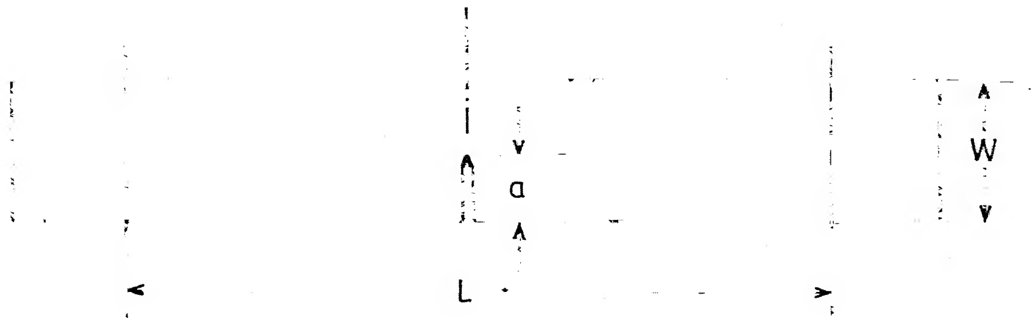
TABLE - 2

Properties of QIL and CPL specimen subjected to bending load

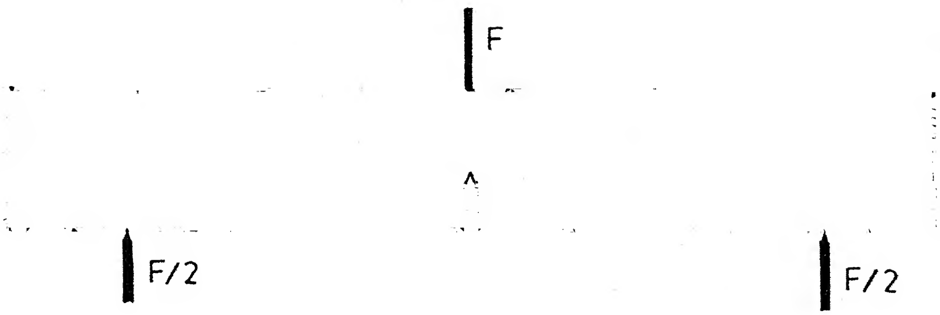
Property	QIL	CPL
Volume fraction of fibres	46.7%	43.7%
Moduli of Elasticity		
Longitudinal	18.36 GPa	23.96 GPa
Transverse	19.1 GPa	28.41 GPa
Ultimate Tensile Strength		
Longitudinal	240 MPa	325 MPa
Transverse	240 MPa	300 MPa

3.2 SPECIMEN DETAILS:

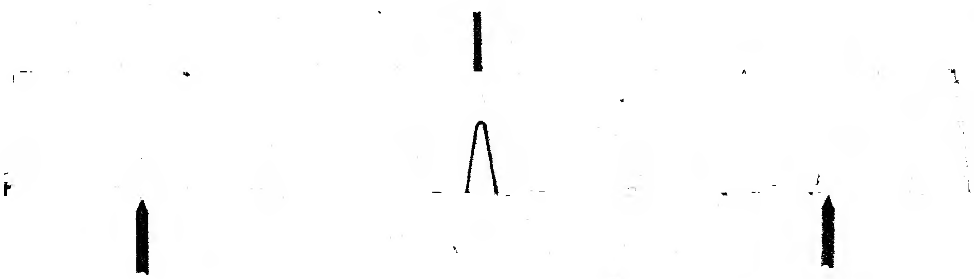
Single Edge Notch (SEN) specimens were 25 mm wide, 3.9 mm (for Quasi Isotropic Laminates) and 4.0 mm (for Cross-Ply Laminates) thick and span was at least 3 times the width of the specimen. The specimen configuration is shown in Fig.(3.3). The initial notches were machined using a 0.25 mm thick slit cutter and their lengths varied from 10.0 mm to 17.5 mm (that is a/w = 0.4 to 0.7). A lathe available in the laboratory was suitably modified for cutting notches. The experimental set-up is shown in Fig. (3.4).



(a) Specimen configuration



(b) A cracked body with constant load



(c) A cracked body with constant displacement applied

Fig. 3.3 Specimen details.

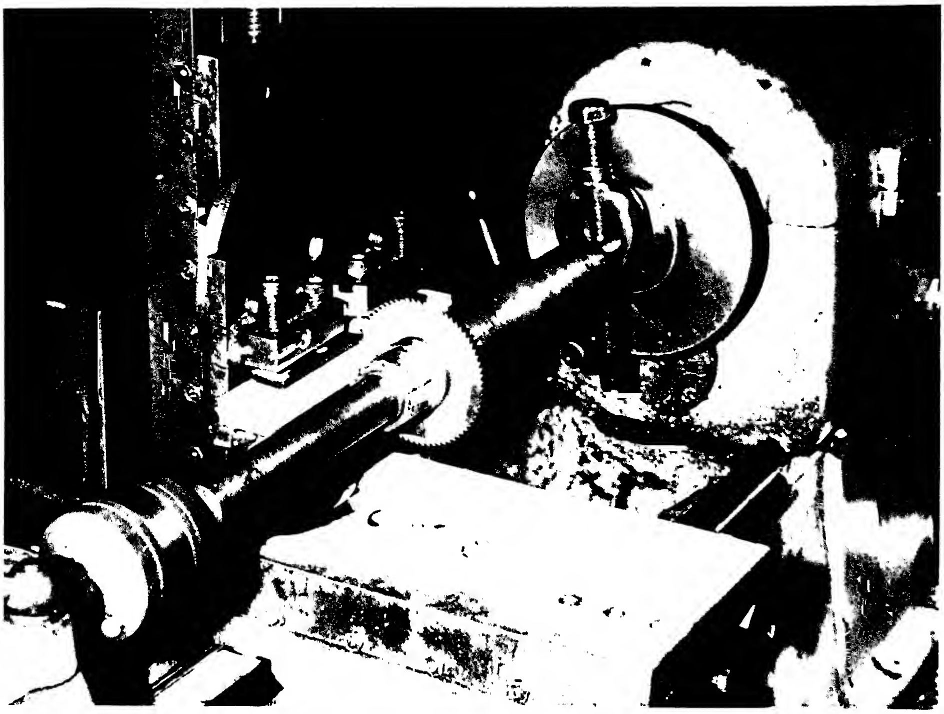


Fig. 3.4 : Experimental set-up for cutting notches

3.3 TESTING SYSTEM:

The three point bend tests for obtaining fracture toughness were conducted on SEN specimens in a 10 Ton MTS machine. The general experimental arrangement is shown in Fig. (3.5 and 3.6). The upper point is fixed and the lower supports move in a vertical direction. The tests were conducted in displacement controlled mode. Instantaneous value of load, displacement of lower support were recorded through X-Y recorder. At least five specimens were tested for each crack-length.

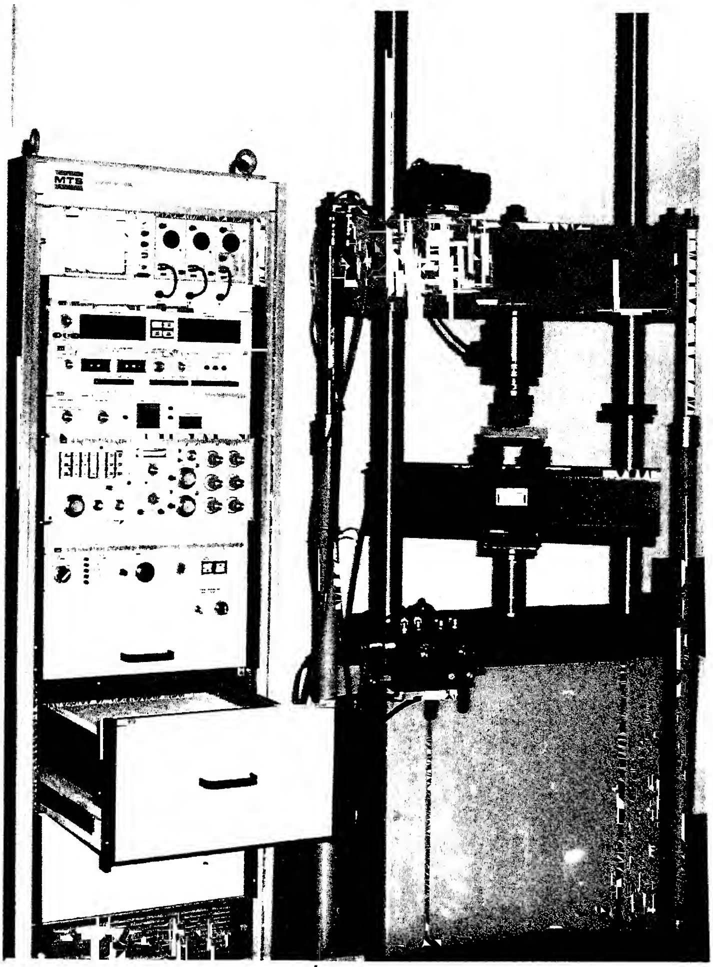


Fig. 3.3 : Experimental arrangement
on MTS machine

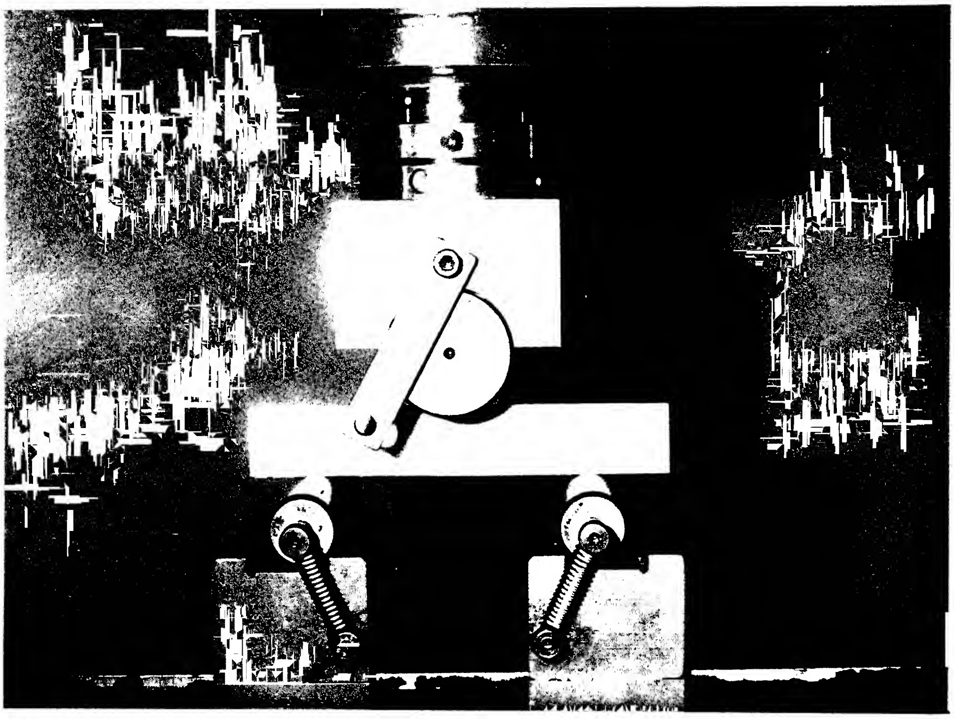


Fig. 3.6 : A typical 3-point bend test arrangement

CHAPTER - IV

RESULTS AND DISCUSSIONS

In this chapter, discussion is based on two portions of the present work. Firstly, discussions is on the results obtained from Quasi Isotropic Laminates (QIL) subjected to tension with those of Srinivasan's results [13], which were also for the determination of J-integral on QIL subjected to tension.

Secondly, the discussion is on the determination of J-integral by Estimation Procedure (EP) and Energy Rate Interpretation (ERI) for both Quasi Isotropic Laminate (QIL) and Cross Plied Laminate (CPL) subjected to bending load.

4.1 TENSION TESTS:

Srinivasan [13] has tested both QIL and CPL under tension. He has obtained J-integral using ERI technique. He has also obtained J_{1c} for both QIL and CPL. For CPL, the J_{1c} obtained by Srinivasan for all a/w has a constant value of 22.65 kJ/m^2, while for QIL, he has obtained two different values of J_{1c} for two

ranges of a/w. The value of J_{1c} obtained by him for QIL, for $a/w \leq 12.5$ is 23.75 kJ/m^2 and that for $a/w > 12.5$ is 46.5 kJ/m^2. It can be noted here that the value of J_{1c} obtained by Srinivasan for $a/w > 12.5$ is almost double the value of J_{1c} for $a/w \leq 12.5$.

Agarwal, Patro and Kumar [12] have shown that J_{1c} is independent of a/w if appropriate extrapolation procedure is used for small a/w. Due to this reason, Srinivasan's results for QIL raised some doubts about their accuracy. Therefore, more fracture tests in tension were performed on QIL. The load-displacement curves are shown in Fig. (4.1). While Fig. 4.2 gives the curve for critical displacement, Fig. 4.3 gives the variation of strain energy per unit thickness with displacements. The geometry and dimensions of the test specimens were the same as these used by Srinivasan. The present tests show that the value of J_{1c} for all a/w ratios is 23.8 kJ/m^2 using Energy Rate Interpretation (Fig. 4.4). This seems to be agreeable within experimental errors. Fig. 4.5 shows a qualitative comparison of the values of J_{1c} obtained for CPL and QIL under tension by Srinivasan with that of J_{1c} obtained by the author for QIL under tension.

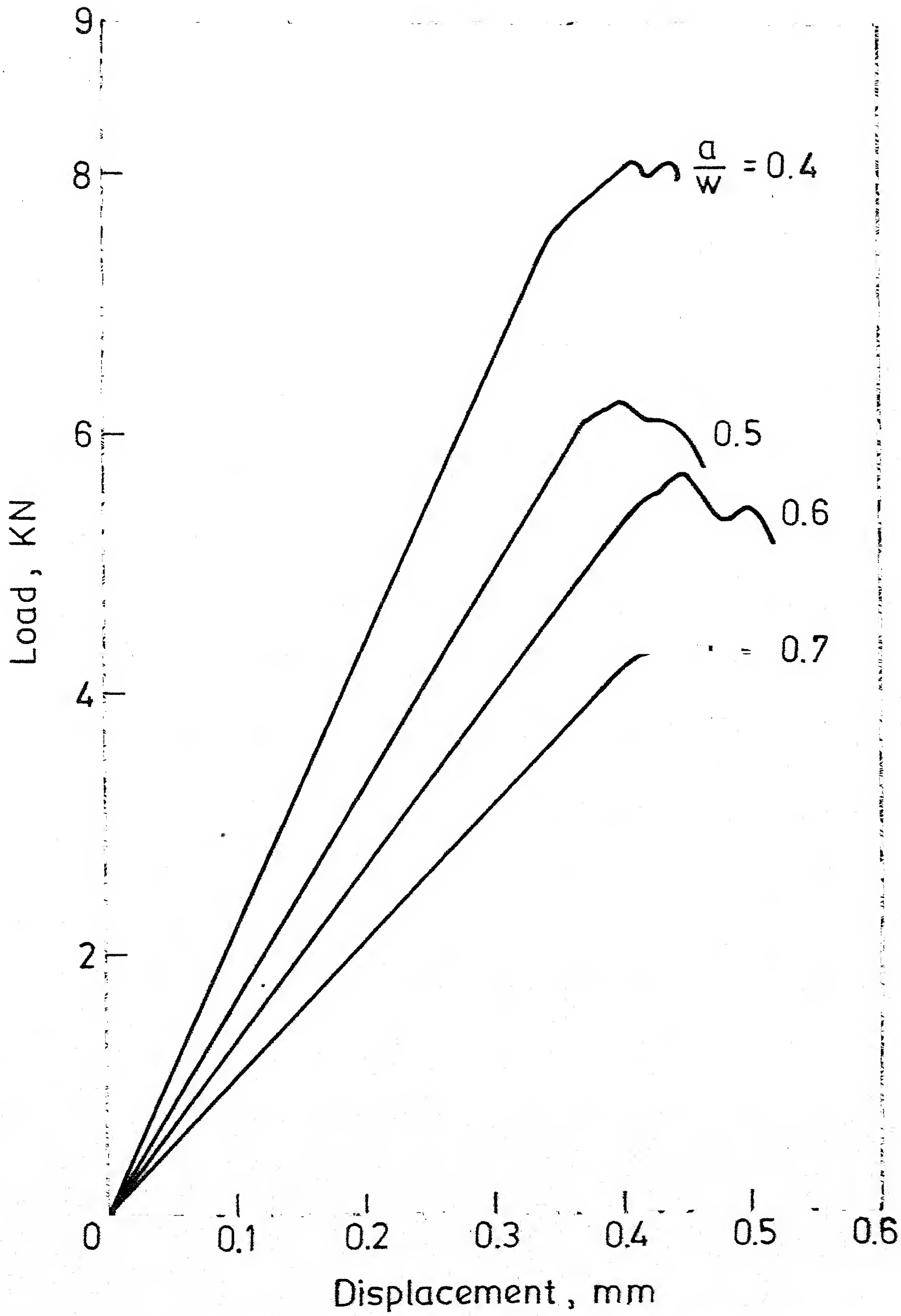


Fig. 4.1 Load-displacement curve for QIL under tension.

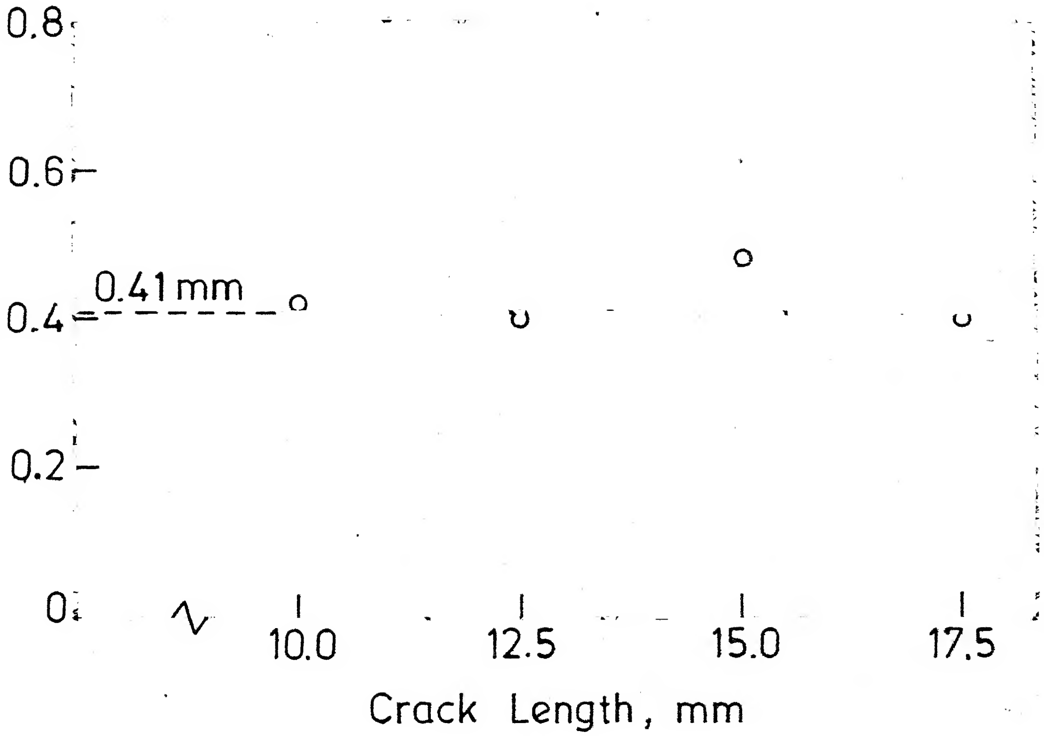


Fig. 4.2 Variation of critical displacement with crack length for QIL under tension.

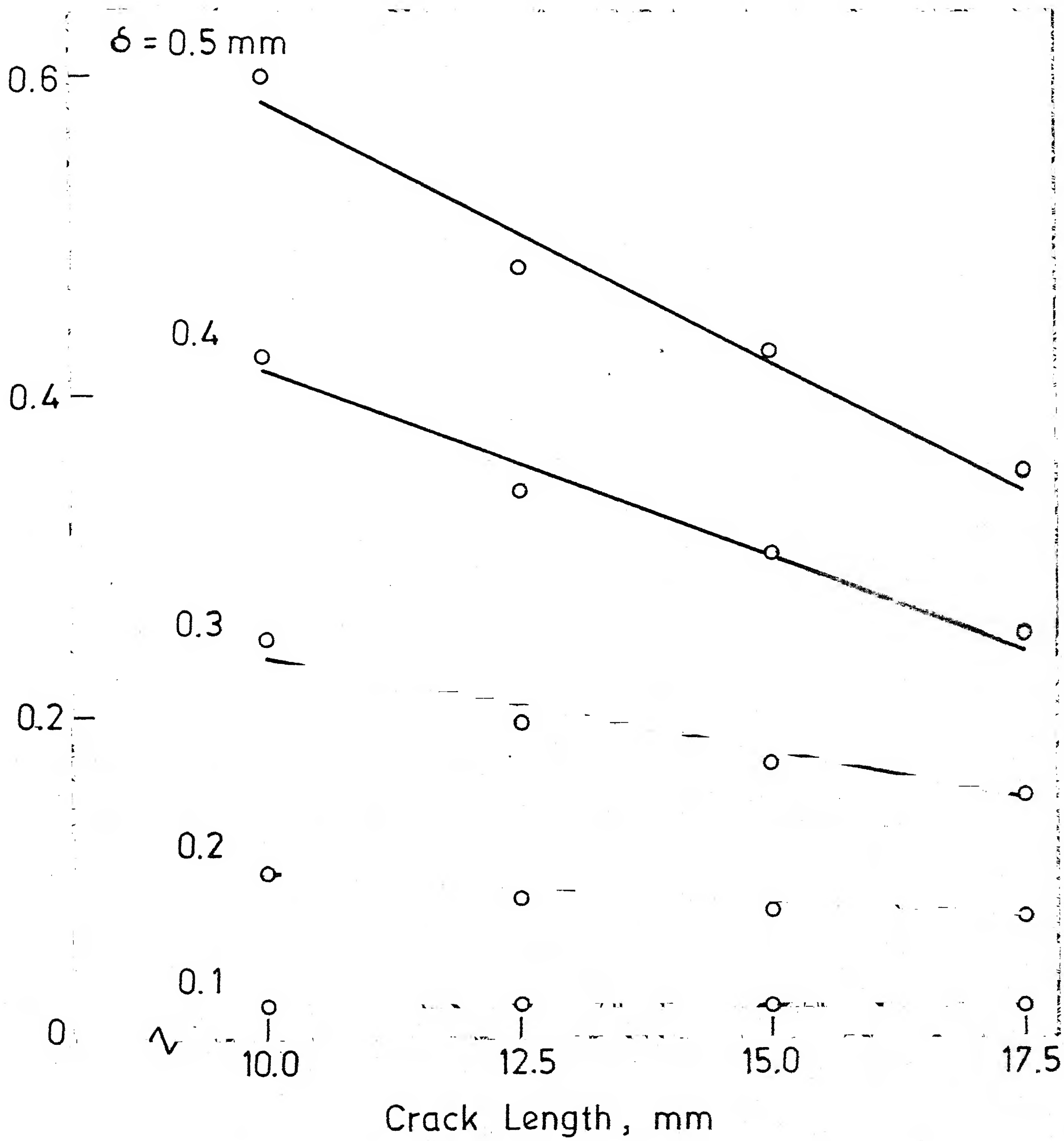


Fig. 4.3 Variation of strain energy per unit thickness with displacement for Quasi Isotropic laminate under tension.

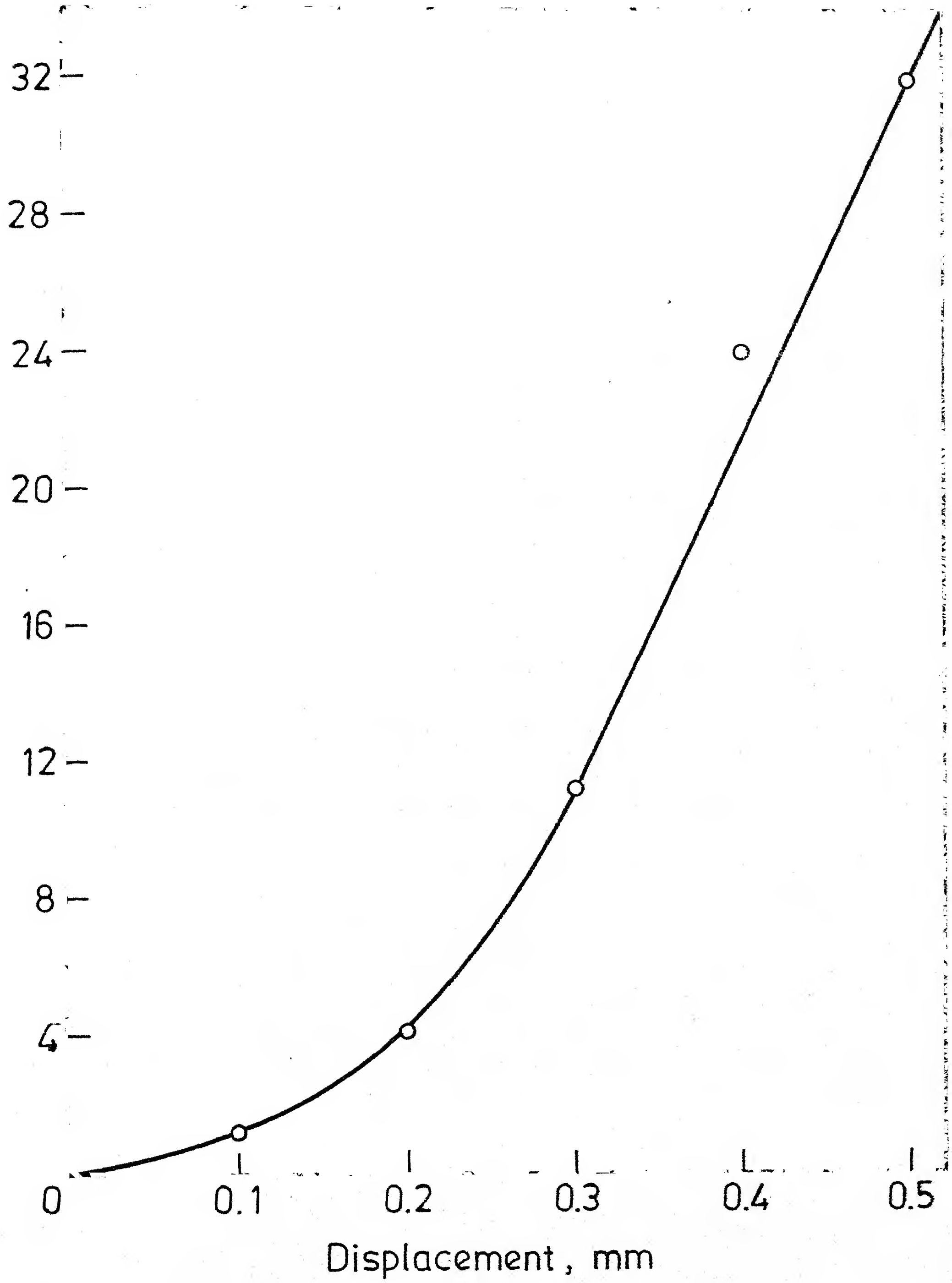


Fig. 4.4 J-Integral as a function of displacement for QIL using ERI technique.

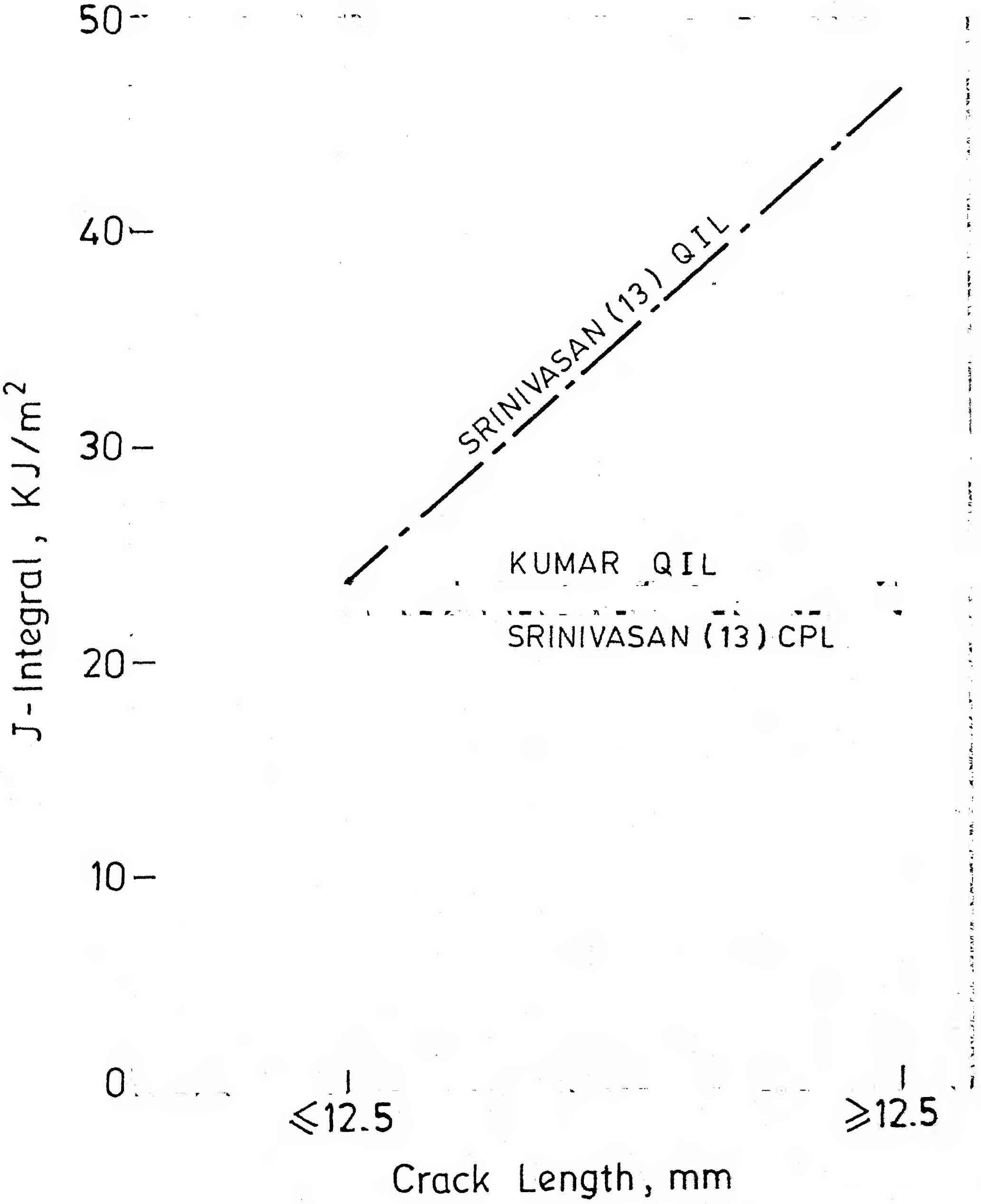


Fig. 4.5 Comparision of J for Quasi Isotropic laminate under tension by Srinivasan's and Kumar's result.

4.2 BENDING TEST:

The fracture toughness tests under bending load for the experimental determination of J-integral were conducted on:

(i) Quasi Isotropic Laminate (QIL)

(ii) Cross Plied Laminate (CPL)

In this section, the determination of J-integral by both Energy Rate Interpretation and Estimation Procedure is discussed. An attempt has also been made to compare the two procedures.

4.2.1 : FRACTURE BEHAVIOUR OF QIL AND CPL:

Specimens of QIL with $[0/\pm 45/90]_{2s}$ configuration and CPL with $[0/90]_{4s}$ configuration have been tested under bending for fracture toughness determination. Typical load-displacement (at load points) curves for specimens with different initial crack lengths are shown in Figs. 4.6 and 4.7.

The tests were conducted under displacement controlled conditions so that the load displacement behaviour beyond maximum load is also clearly indicated.

Photographs of failed specimens in Fig. 4.8 and 4.9 show the extent of damage in QIL and CPL specimens of different crack lengths.

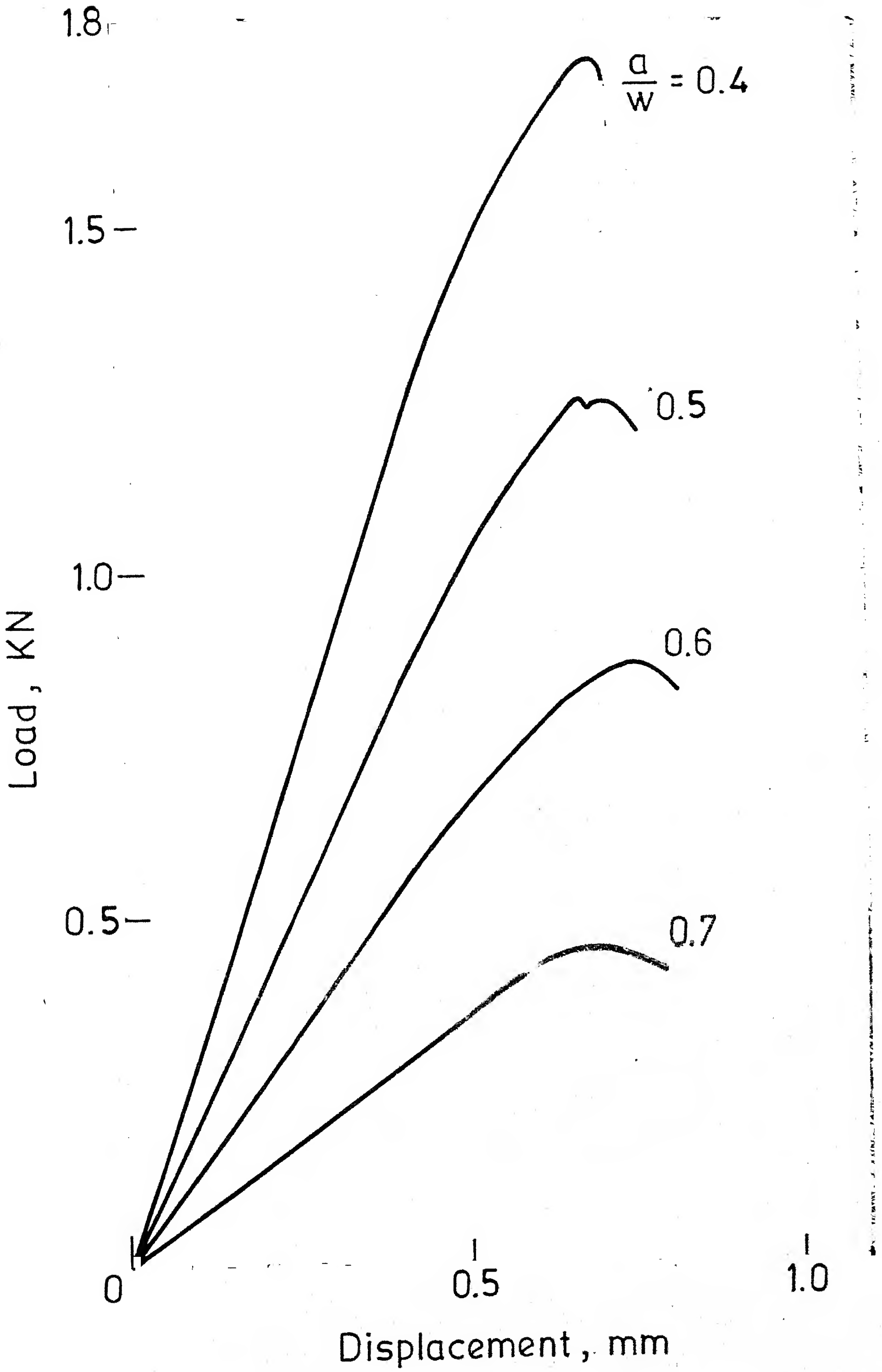


Fig. 4.6 Load displacement record for $[0/\pm 45/90]_{2S}$ glass fibre reinforced epoxy laminates.

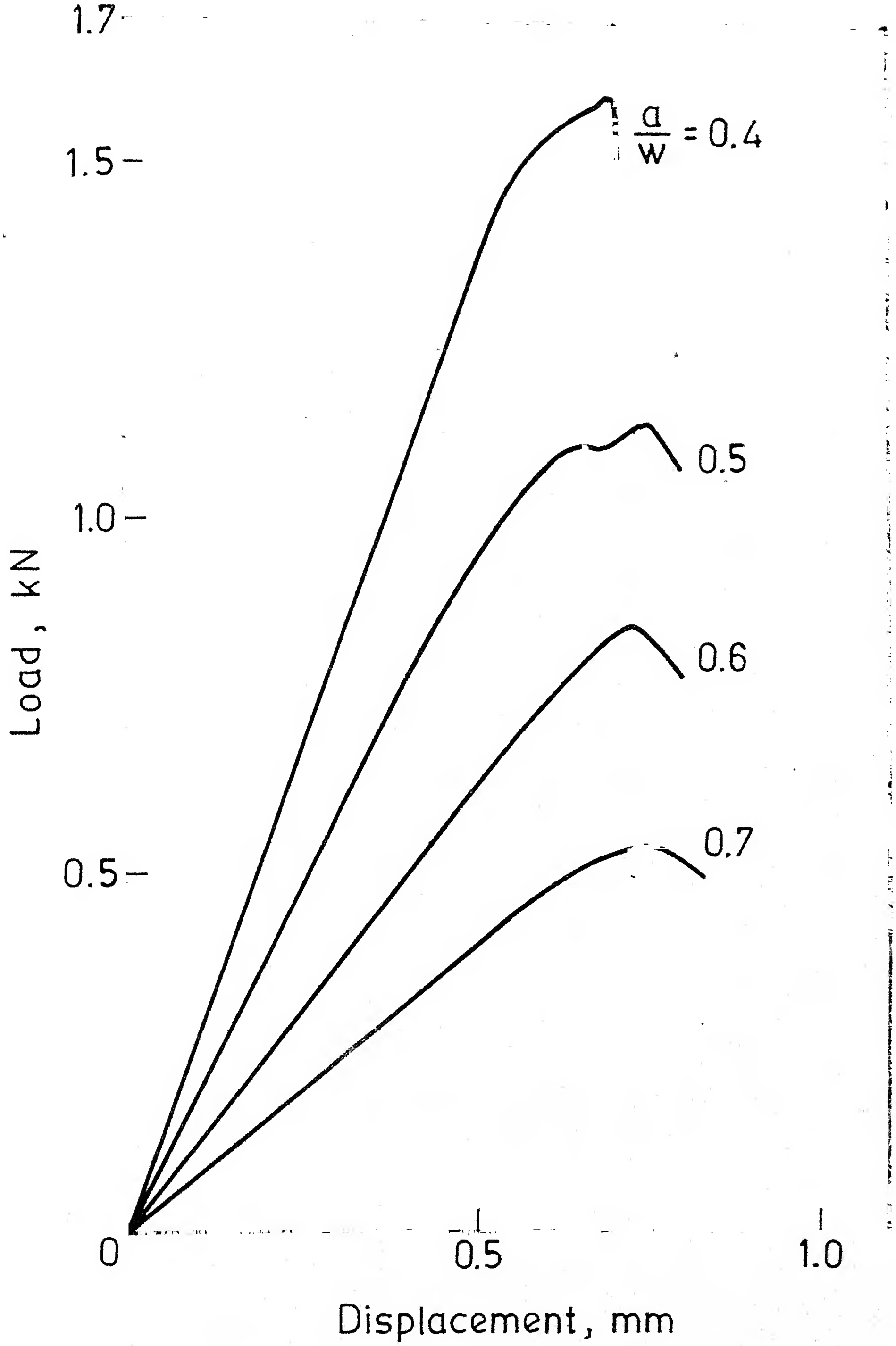


Fig. 4.7 Load displacement record for $[0/90]_{4S}$ glass fibre reinforced epoxy laminates.

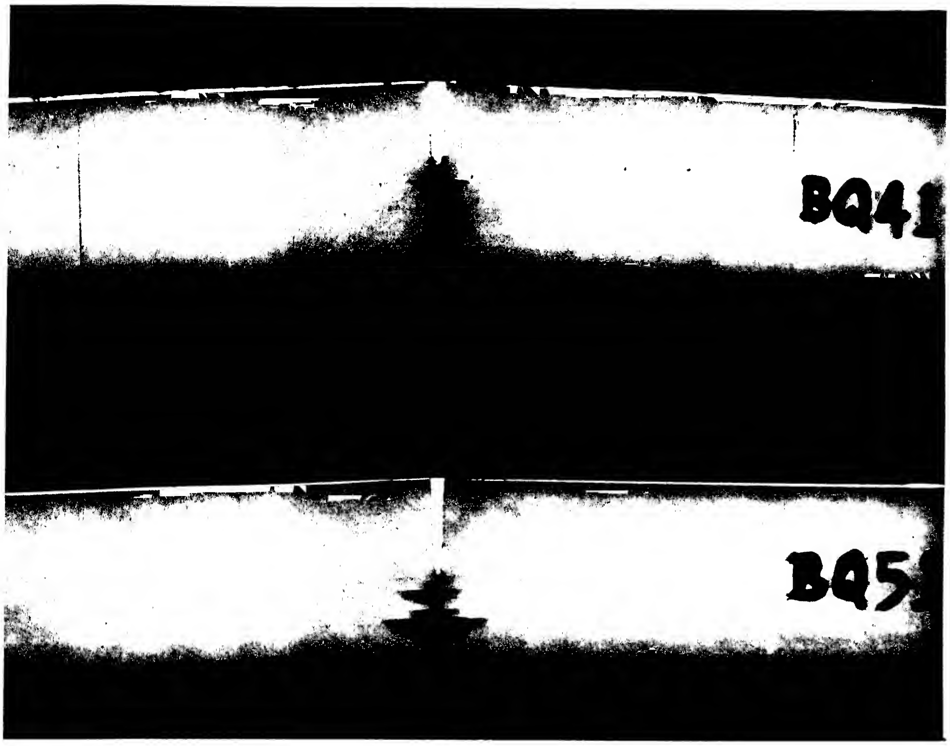


Fig. 4.8 : Transmitted light photograph of two specimens $[0/\pm45/90]_{2s}$ configuration with different crack lengths.

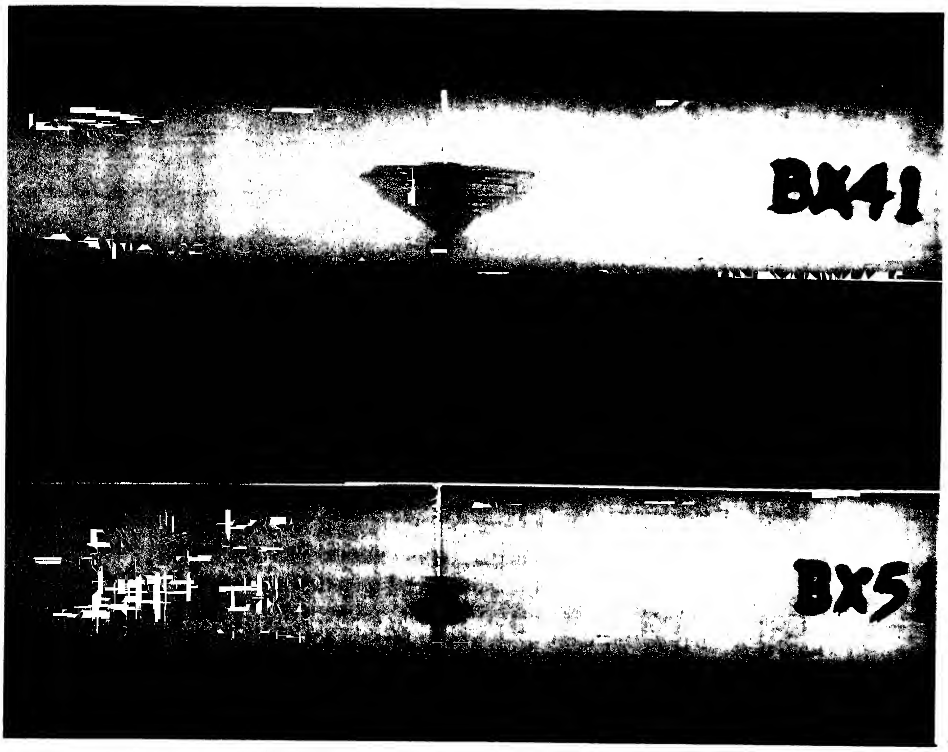


Fig. 4.9 : Transmitted light photograph of two specimens $[0/90]_{4s}$ configuration with different crack lengths

The load deflection curves (Figs. 4.6 and 4.7) for both QIL and CPL show a similar behaviour for all a/w ratios. This type of behaviour is different from that observed by Patro et al [12] for short fibre composites and by Srinivasan for QIL and CPL. They had observed that for small initial crack length there is a general material damage away from crack tip which causes a difference in behaviour between small and large crack length specimen. However, the present tests were performed in bending while the earlier cited tests were in tension. In bending the maximum stress (and bending moment) occurs at mid-span and the stresses away from mid-span are low, while in tension, average stresses are same on all cross-sections which cause general material damage.

The photographs of failed specimens (Fig. 4.8 and 4.9) also show that the damage is confined to the vicinity of crack-plane. The similarity in the load-deflection curves for both QIL and CPL seems to be correct.

The critical displacement has been defined as the displacement at which significant damage develops at the crack tip and the crack starts to grow catastrophically. It coincides with that of the maximum load [11].

The constant value of critical displacement was found to be 0.70 mm for QIL and 0.74 mm for CPL as shown in Figs. 4.10 and 4.11.

4.2.2 : DISCUSSIONS ON THE RESULTS OBTAINED BY EP AND ERI:

As explained earlier the value of J is calculated by both Energy Rate Interpretation and by Estimation Procedure.

In the Estimation Procedure, the formula used is

$$J = \frac{2U_T}{B(w-a)} \tag{4.1}$$

where, U_T is the total energy of the specimen, which is the area under the curve. For each a/w ratio, U_T at various displacement (with increment of 0.1 mm) is obtained, which is simply the area under that incremental portion of the curve for a particular a/w ratio. J is now computed by using formula (4.1). As stated earlier, for comparison sake, to ascertain the value of J the energy rate interpretation technique has also been used. In this procedure the J-integral can be interpretted as the difference in potential energy between two identically loaded bodies having infinitesimally differing crack lengths

$$J = - \left. \frac{dU}{da} \right|_{\text{constant displacement}} \tag{4.2}$$

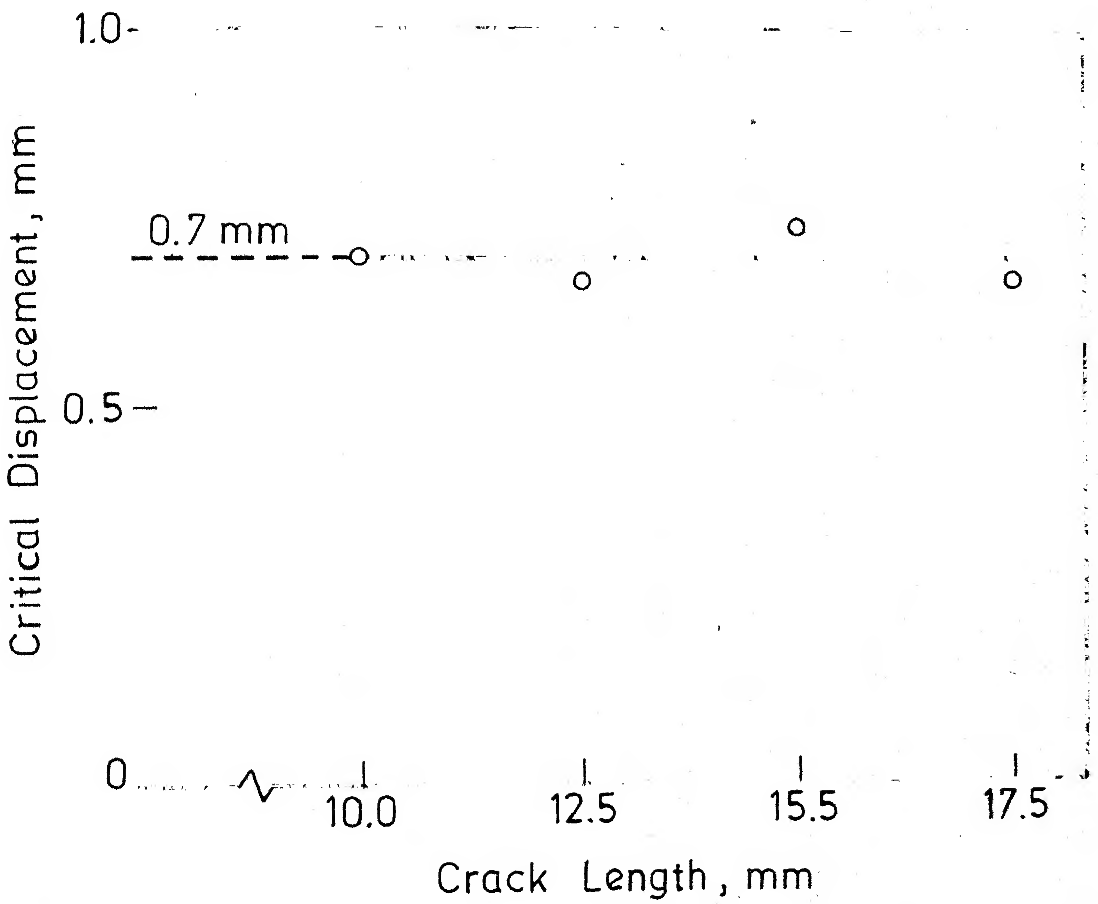


Fig. 4.10 Variation of critical displacement with crack length for Quasi Isotropic laminate.

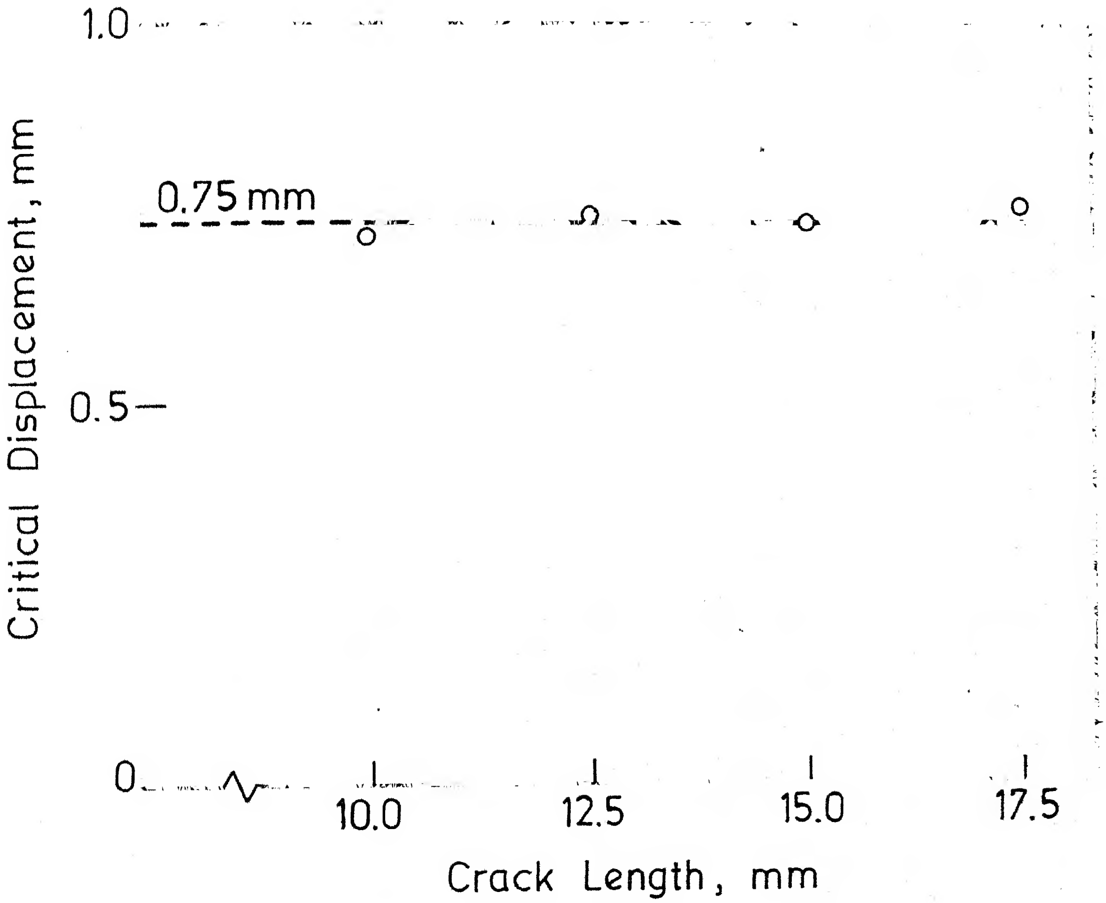


Fig. 4.11 Variation of critical displacement with crack length for cross plied laminate.

where U is the potential energy per unit thickness of the body and 'a' the crack length. Also when the displacement is kept constant for evaluating J, the potential energy U, reduce to the area under the load deflection record and is equal to the strain energy [11]. Thus the areas under the load displacement curves are first obtained at intervals of 0.10 mm displacement and plotted against crack length for several displacements (Figs. 4.12 and 4.13). For a given displacement the energy absorbed by a specimen decreases as the crack length increases (Figs. 4.12 and 4.13) because, smaller loads are required. The plots of energy absorbed have been approximated by straight lines and it can be seen that the deviation is not much. The J-integral is obtained from eqn. (4.2) through the slope of the energy curve in Figs. 4.12 and 4.13.

Fig. 4.14 and 4.15 show the value of J-integral calculated by both Estimation Procedure and Energy Rate Interpretation.

The values of J-integral obtained through Energy Rate Interpretation is represented by one solid curve, while three different sets of points represent the value of J-integral obtained by Estimation Procedure for crack lengths from 12.5 mm to 17.5 mm.

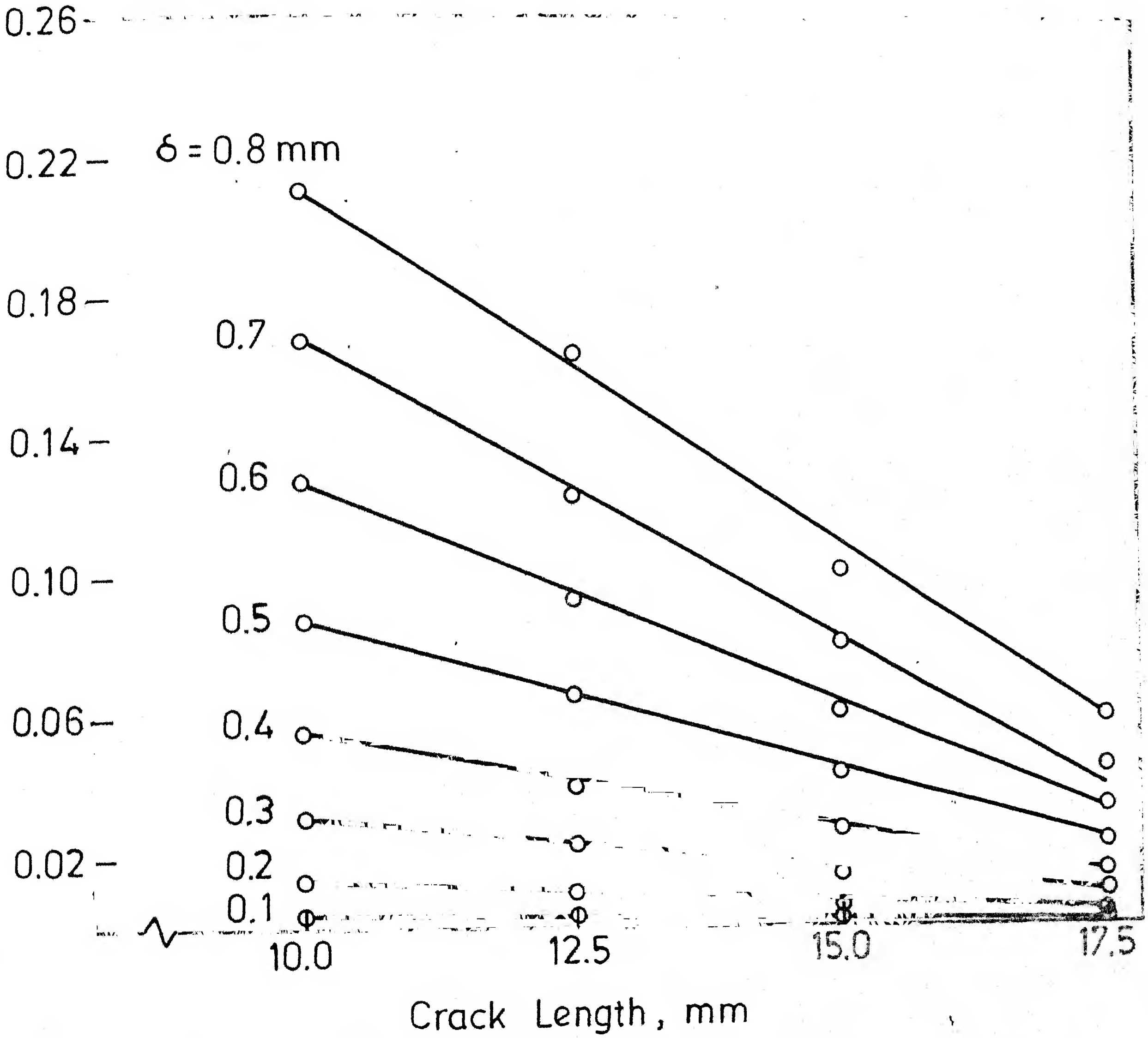


Fig. 4.12 Variation of strain energy per unit thickness with displacement for Quasi Isotropic laminate.

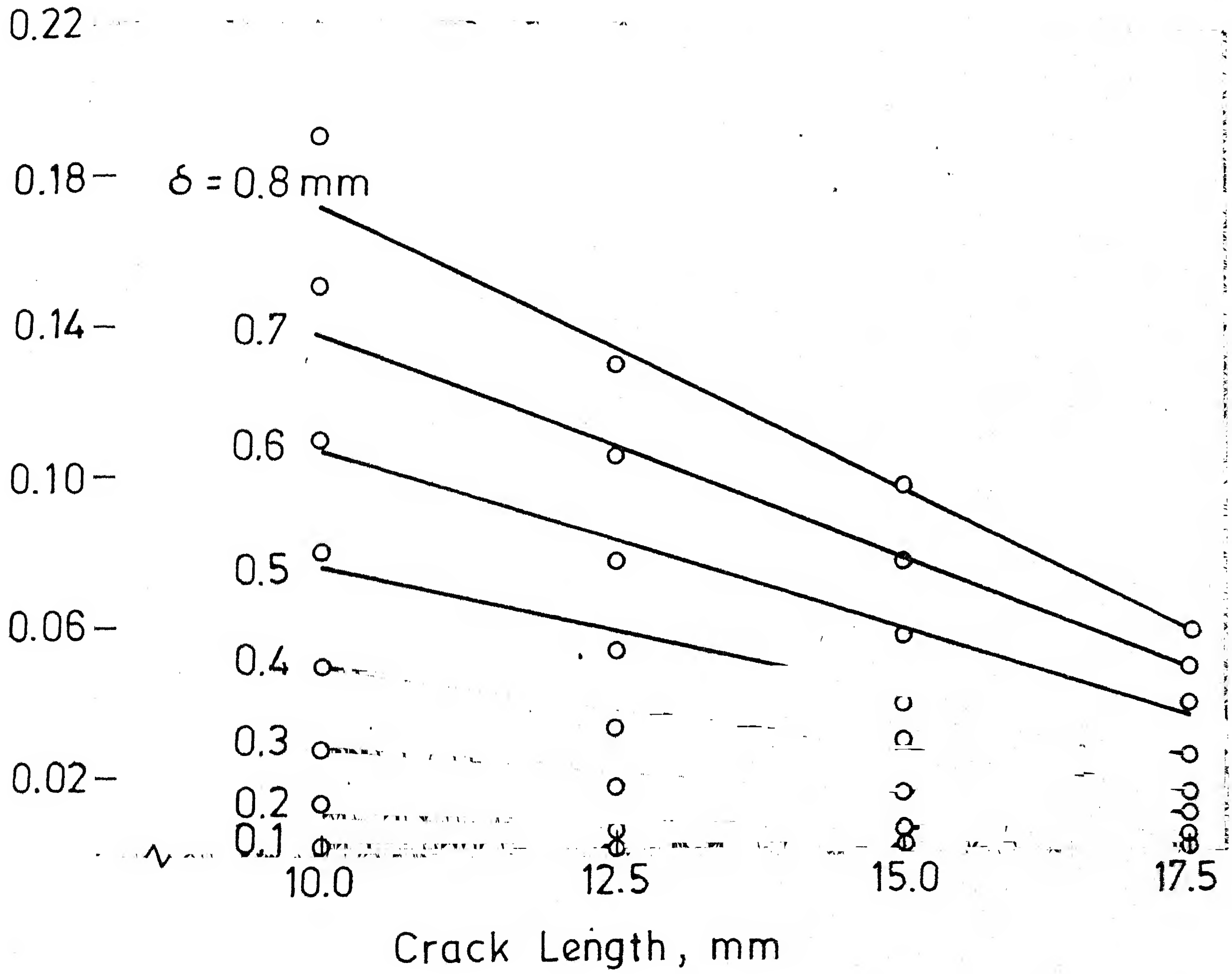


Fig. 4.13 Variation of strain energy per unit thickness with displacement for cross plied laminate.

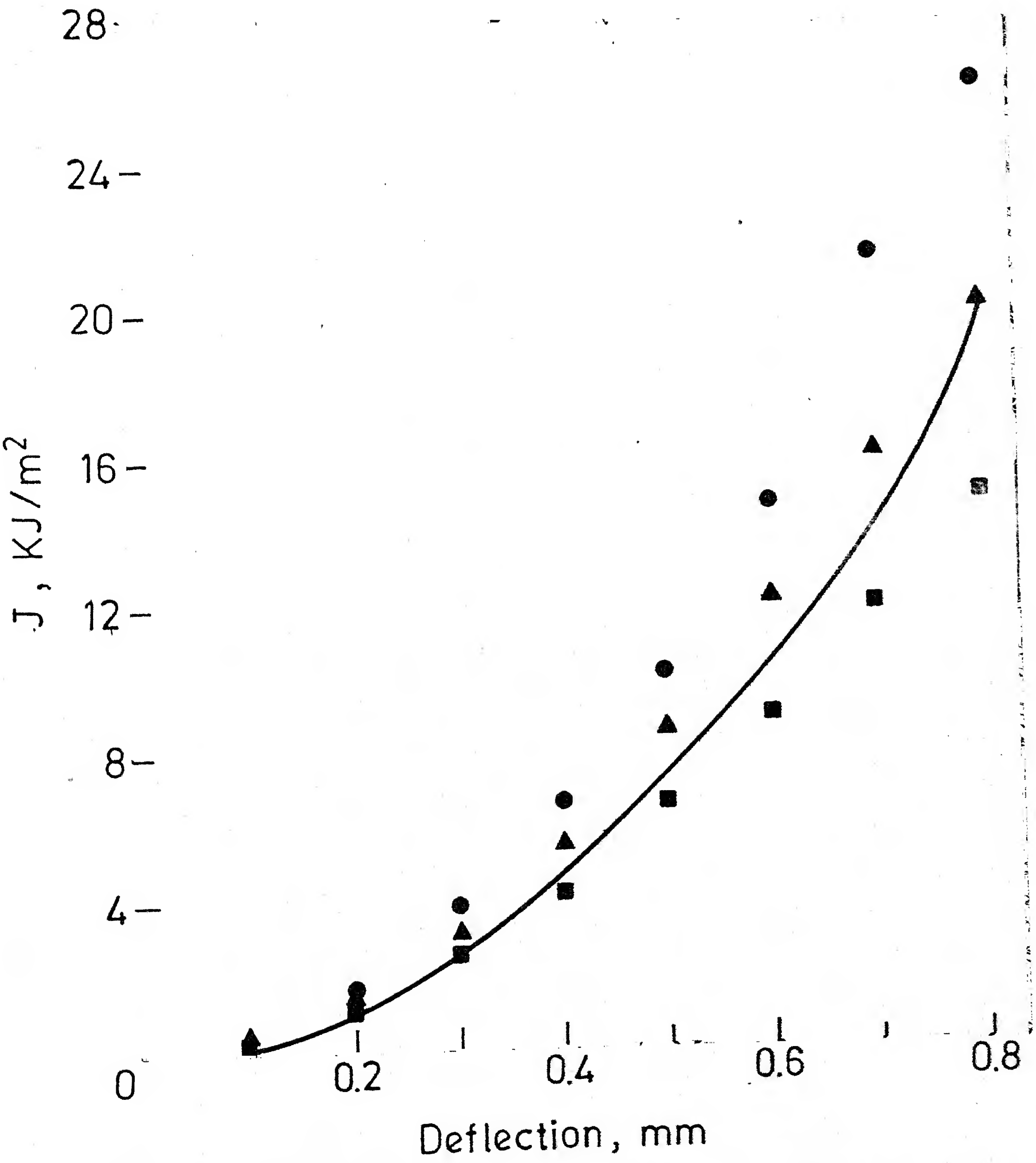


Fig.4.14 Comparison of the value of J-integral by Estimation Procedure and Energy Interpretation Technique for Quasi Isotropic laminates.

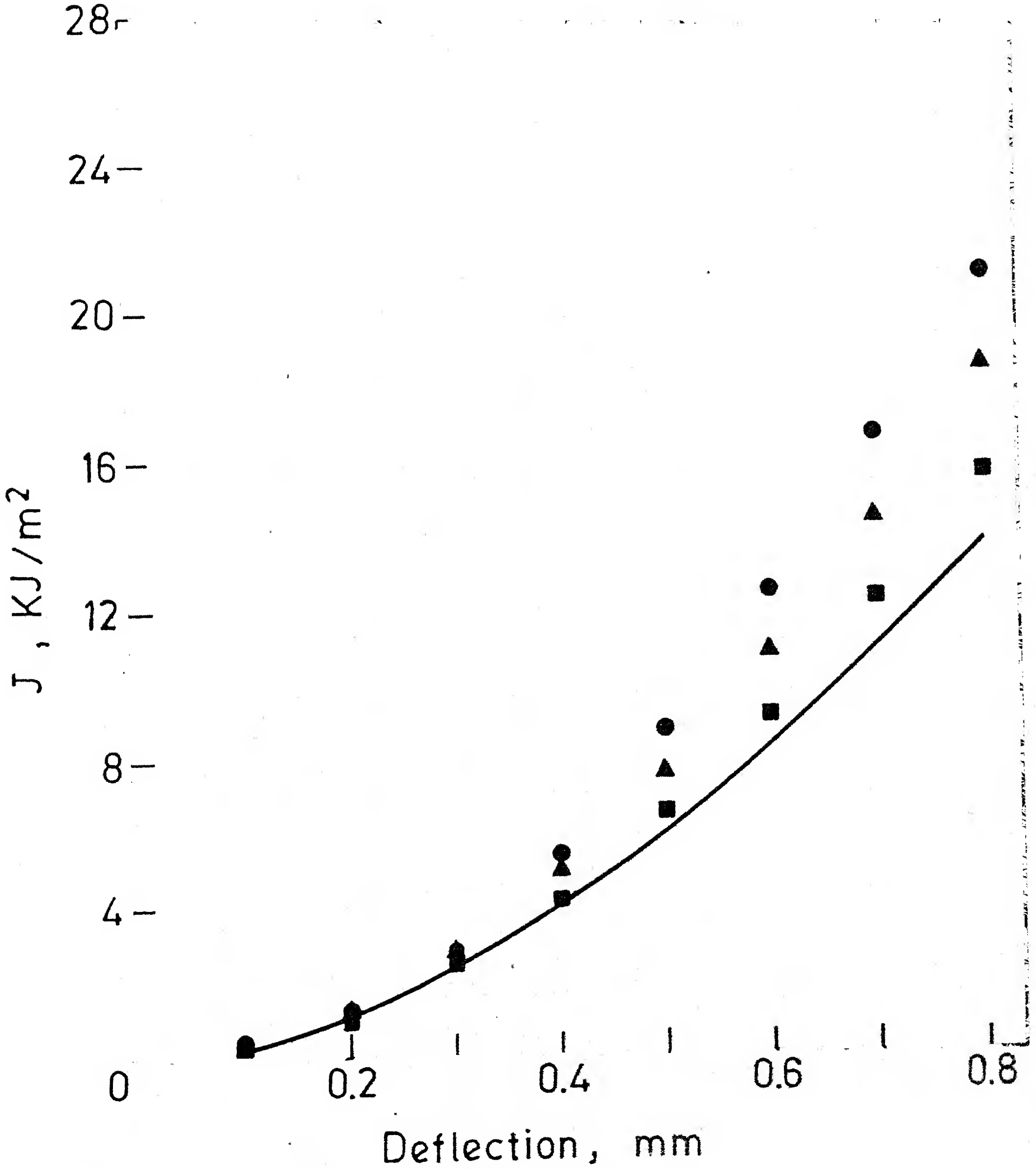


Fig. 4.15 Comparison of the value of J-integral by Estimation procedure and Energy Interpretation Technique for cross plied laminates.

Consolidation of the results obtained by these two procedures give rise to table 3, which presents the value of J_{1c} for both QIL and CPL subjected to bending. The table represents the value of J_{1c} obtained by both Estimation Procedure and Energy Rate Interpretation Technique.

TABLE-3

	Property		Quasi Isotropic Laminate QIL	Cross Plied Laminate CPL
J_c kJ/m^2	Estimation Procedure EP	a (12.5 mm	21.6	18.2
		(15.0 mm	16.2	16.2
		(17.5 mm	12.0	13.6
	Energy Rate Interpretation ERI		14.0	12.2

Design based on conservative value of J-integral would be a safe design. It is difficult to say whether Estimation Procedure or Energy Rate Interpretation give conservative values of J-integral. Because, we have seen (Table 3) that Estimation Procedure gives only slightly different values compared to the value obtained from energy rate interpretation. It is to be noted here, that in energy rate interpretation

technique, the plots of energy absorbed have been approximated by a straight line, which may give rise to inaccuracies in the result and this may be the difference.

With lots of unknown parameters and with the behaviour of composites not fully understood, it is difficult to arrive at a procedure which can give conservative value of J and that too, with the present insufficient data.

Nevertheless, a distinct advantage seems to exist in the Estimation Procedure. That is, it gives a very easy method to calculate the value of J-integral and which is quite comparable to the J values obtained through Energy Rate Interpretation.

However, lot more is to be studied regarding how the known and unknown parameters influence the J-integral while adopting the Estimation Procedure.

The present work is, therefore, the first step towards establishing a suitable procedure for specimens subjected to bending load.

CHAPTER - V

CONCLUSION AND SCOPE FOR FURTHER WORK

5.1 CONCLUSION:

Fracture behaviour of Quasi Isotropic Laminate under bending have been investigated. Fracture toughness tests were conducted on Single Edge Notched specimens subjected to bending load. J-integral was evaluated using both Energy Rate Interpretation and Estimation Procedure. Estimation Procedure is found to be easy and simple and the value of J-integral obtained by it match very well with the value of J-integral obtained by Energy Rate Interpretation. Fracture toughness tests on Quasi Isotropic Laminates under tension were also conducted. This was done to validate that J_{1c} is independent of a/w.

5.2 SCOPE FOR FURTHER WORK:

The J-integral approach applied here to Quasi Isotropic Laminates and Cross Plied Laminates show a great promise. Both the methods, Estimation Procedure and Energy Rate Interpretation, used here produces results which are quite closer. For greater confidence

further investigations should be carried out using different materials and specimen variables. Some of the aspects which may be investigated are mentioned below:

1. The effect of using U_{nc} instead of U_T can be studied while calculating the value of J using Estimation Procedure.

2. Determination of J-integral by both EP and ERI can be applied to other reinforcement systems such as woven fabric.

3. Other types of specimen, such as compact tension specimen should also be tested for fracture toughness parameter using both EP and ERI techniques.

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